NASA FORM 1329	**Inventions and Contributions Board *Space Act Award Application***	**NASA Case Number: ARC-15794-1**	**Date:**
SECTION I *SPACE ACT AWARD APPLICATION*			
TITLE Generation II Neural Networks for Intelligent Flight Control System, Load ISR_ARTS II_OFP_4-1			

1. DESCRIPTION.

a. Briefly describe the contribution. In addition, if peer-reviewed publications by contributors have been accepted on this topic in refereed journals or for refereed conference papers, please attach a copy with this form as a supplement.

This award nomination is for the Generation II (Gen II) Neural Networks for the Intelligent Flight Control system (IFCS). Major control surface failures or airframe damage greatly hinder the ability of a pilot to recover control of an aircraft, and in some instances can result in complete loss of control in flight. The IFCS team has integrated an innovative neural network technology with state-of-the-art control algorithms to correctly adjust aircraft control to maintain the best possible flight performance during an unexpected failure. A direct adaptive approach incorporates neural networks that are applied directly to the flight control system feedback errors and which provides adjustments to improve aircraft performance.

The objective of NASA's Intelligent Flight Control System (IFCS) program is to develop and flight test control schemes that enhance control during a primary control surface failure or aerodynamic change due to a failure or modeling errors. IFCS exploits a revolutionary technological breakthrough in aircraft flight controls that efficiently optimizes aircraft performance under both normal and failure conditions. The system incorporates self-learning neural network concepts into flight control, enabling a pilot to maintain control and safely land an aircraft that has suffered a major systems failure or damage to the airframe. The IFCS testbed aircraft, shown below, is a fly-by-wire canard-equipped F-15B.

On 14 February 2006, the IFCS project achieved its goal of the development and validation of a Generation II direct adaptive neural network-based flight control system. Following a series of incremental tests to validate nominal (unaugmented) flight control system performance, neural network (IFCS) responses, and failure insertion modes, Generation II ICFS software was engaged at Mach 0.75 in the presence of a failure, in the first demonstration of assistive adaptive control of a piloted aircraft. The system was evaluated in both nominal and failure conditions. Results and feedback from the test pilots indicate IFCS met all expectations, demonstrating improved handling qualities through a series of challenging maneuvers. The IFCS tests validated the predicted simulations of neural network responses and the direct adaptive control of the vehicle to adjust for the failures and restore degraded handling qualities back to nominal performance.

NASA Dryden Flight Research Center Photo Collection
http://www.dfrc.nasa.gov/Gallery/Photo/index.html
NASA Photo: EC03-0231-1 Date: August 27, 2003 Photo By: Jim Ross

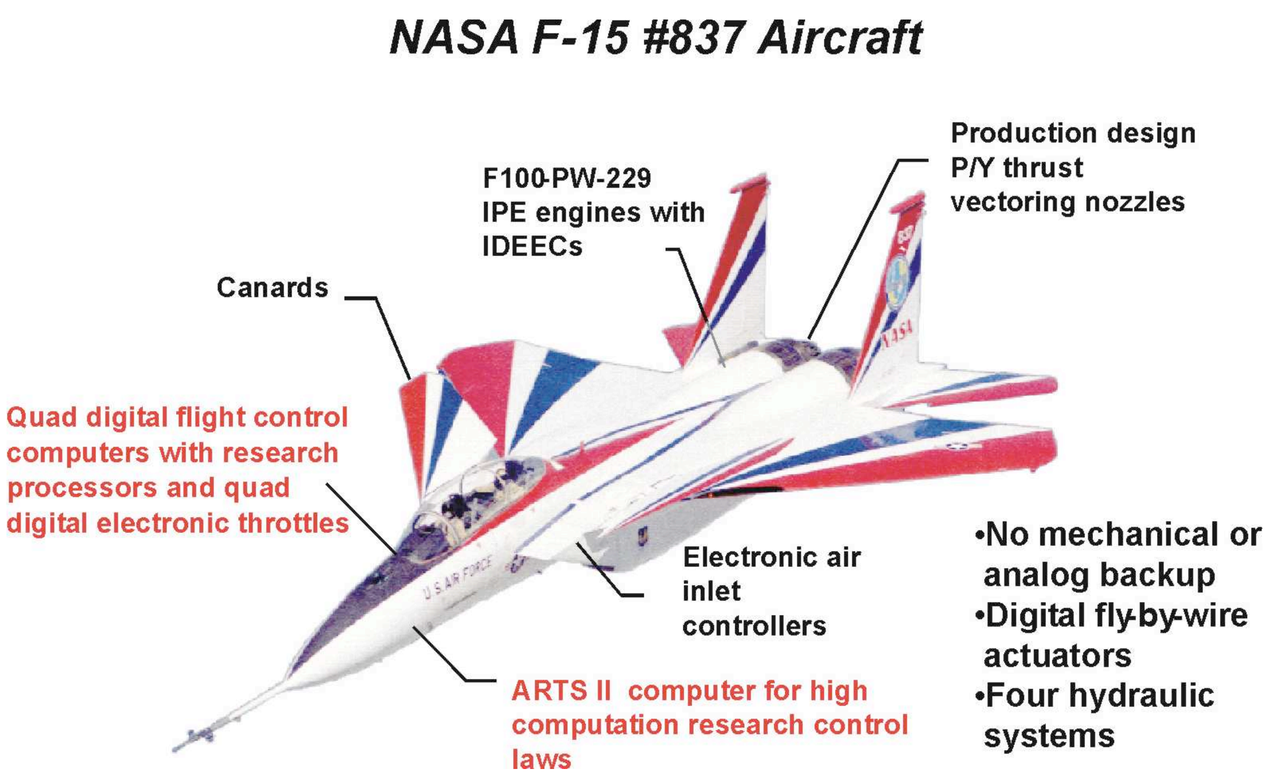
NASA Dryden's highly-modified F-15B aircraft, tail number 837, serves as an Intelligent Flight Control System (IFCS) research testbed aircraft.

The first flight phase, using Generation I control software, required aerodynamic parameter identification. Generation I IFCS flight tests, flown in 2003, used onboard algorithms to identify changes in aerodynamic characteristics. Neural networks organized and mapped these aerodynamic changes, and provided the flight control system with that information. The flight control system then used this information to stabilize the aircraft and provide specific flying characteristics. The Generation I system was flown in an open loop. Risk reduction flights were flown in 2002 that provided information to develop and refine the system prior to actual IFCS tests.

The goal of the second flight phase is to evaluate the Generation II neural flight control system that provides adaptive control without explicit parameter identification. From a project perspective the specific objectives for Gen II are to (1) Implement and fly a direct adaptive neural network-based flight controller; (2) Demonstrate the ability of the system to adapt to simulated system failures by suppressing transients associated with the failure; (3) Re-establish sufficient control and handling of the vehicle for safe recovery; and (4) Provide flight experience for development of verification and validation processes for flight-critical neural network software.

This software is a direct adaptive system that applies corrections continuously and learns by observing the overall effect on performance. Gen II IFCS flight tests allow the neural networks to take more direct control of the vehicle, working alongside the flight controller to adjust for any shortcomings and functioning more like equal partners with the flight control system. Pre-trained neural networks are used to provide estimates of aerodynamic stability and control characteristics required for model inversion. On-line learning neural networks, working in conjunction with the error controller, are used to compensate for errors and adapt to changes in aircraft dynamics and control allocation schemes.

The Gen II approach does not require (1) information on the nature or the extent of the failure, (2) knowledge of the control surface positions, or (3) information on aerodynamic failures or unmodeled parameters. The tracking controller adds direct adaptive neural network signals to the control law. The neural networks are used to generate command augmentation signals to compensate for errors due to unmodeled dynamics, including dynamics due to damage or failure. The F-15 six-degree-of-freedom simulator was used in the evaluation test, comparing stabilator and canard failure compensation with the neural network algorithm. The canard failure emulates a change in pitching moment due to angle of attack, and is considered an aerodynamic-type problem/malfunction due to modeling errors or damage. Flight demonstration started early in the year 2006, on the NASA F-15 tail number 837. Similar to earlier IFCS risk reduction work, risk reduction flights were flown earlier in 2005 in preparation for the Generation II tests.



Attached technical papers:

- John Kaneshige, John Bull, and Joseph J. Totah. “Generic Neural Flight Control and Autopilot.” American Institute of Aeronautics and Astronautics (AIAA-2000-4281)
- John Kaneshige and Karen Gundy-Burlet. “Integrated Neural Flight and Propulsion Control System.” American Institute of Aeronautics and Astronautics (AIAA-2001-4386)
- John J. Burken, Peggy Williams-Hayes, John Kaneshige, and Susan J. Stachowiak. “Adaptive Control Using Neural Network Augmentation for a Modified F-15 Aircraft (January, 2006)

b. In what NASA program, project or mission has this contribution been used or will be utilized and to what extent? (*include any non-aerospace commercialization applications)*

The technology will be utilized in an overall strategy aimed at advancing neural network-based flight control technology for new aerospace systems designs. Many vehicle classes are being considered within the aerospace community, including commercial, fighter, transport aircraft, unmanned air vehicles, and spacecraft. This type of intelligent software can also be used in power plants, automobiles, and other less complicated systems to avoid disasters after equipment failures. The most likely applications are in crewed and uncrewed systems for both military and commercial aviation applications.

Initial program funding was from the Aeronautics Research Mission Directorate, Vehicle Systems Program/Flight and Systems Demonstration Project; CICT Program/ Information Technology Strategic Research Project. The program is currently funded through the Exploration Systems Mission Directorate – Advanced Space Technology Program/Communications, Computing, Electronics and Imaging/A Plug-and-Play Architecture for Real-Time Intelligent Avionics.

Future NASA-specific applications include:

- Aeronautics Research Mission Directorate – Aviation Safety Program/Integrated Resilient Aircraft Control Project. IFCS was recently cited in a $165M/5-year Project Proposal in Integrated Resilient Aircraft Control to NASA’s Aeronautics Research Mission Directorate’s Aviation Safety Program.
- Science Mission Directorate – Suborbital Science Program/Earth Science Capability Demonstration Project. IFCS is currently being considered as part of the Civil UAV Capabilities Assessment (part of Autonomous Mission Management, Contingency Management, and Reliable Flight Systems): http://www.nasa.gov/centers/dryden/research/civuav/index.html

c. Provide details describing how the contribution works or operates relative to system, subsystem, components, etc.

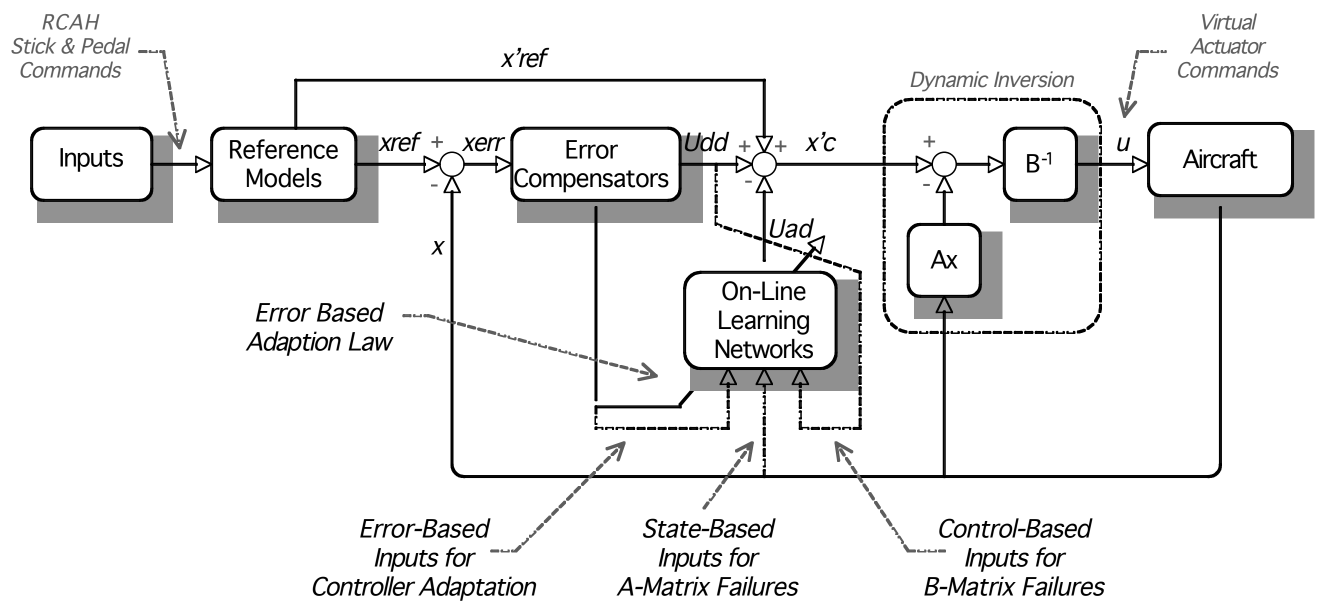
When a failure or large change in aerodynamics occurs, the “normal” control system tries to overcome the errors, but often the failure is too large for the system to handle. However, when the control system can learn (or adapt to) the problem, the chances of landing safely increase. The objective of IFCS is to develop and flight test a neural network control scheme that enhances control during a primary control surface failure or aerodynamic change due to a failure or modeling errors. The system provides adaptive control without explicit parameter identification. This approach does not require (1) information on the nature or the extent of the failure, (2) knowledge of the control surface positions, or (3) information on aerodynamic failures or unmodeled parameters.

IFCS augments a flight control system with a “learning” adaptive integrated neural network subsystem which applies additional signals to the flight controller signals when a failure has occurred, or large errors have built up. When a failure has occurred, the neural network portion will “learn” the failure and augment the controller with information to help stabilize the aircraft. Under normal operating conditions, the system utilizes conventional flight control surfaces, with neural networks used to provide consistent handling qualities across flight conditions and for different aircraft configurations. Under damage or failure conditions, when additional control power is necessary for achieving desired flight control performance, the neural networks add signals to maintain the desired performance.

In this case, the neural network subsystem is used to adapt to changes in aircraft dynamics. Of significant importance here is the fact that this system can operate without emergency or backup flight control mode operations. An additional advantage is that this system can utilize, but does not require, fault detection and isolation information or explicit parameter identification.

The goal of the IFCS neural networks is to enable consistent handling qualities across flight conditions, and in the presence of damage or failures, without requiring extensive gain scheduling or explicit system identification. The on-line learning neural networks work in conjunction with the error compensators, recognizing patterns in the tracking error, and directly adapting the corresponding acceleration commands. By recognizing patterns in the behavior of the error, the neural networks can learn to remove biases through control augmentation commands. Since the neural networks only produce augmentation commands, they can start from an untrained state.

The Generation II neural net IFCS software being nominated here uses an augmented model inversion-based approach, developed by Rysdyk and Calise. This explicit model-following control architecture, shown below, incorporates command filtering reference models to specify desired handling qualities; linear proportional, integral, and derivative (PID) error compensators; and dynamic inversion to compute the necessary actuator commands. Direct adaptive on-line learning sigma-pi neural networks generate command augmentation signals to compensate for model inversion errors, as well as changes for due to damage or failures.

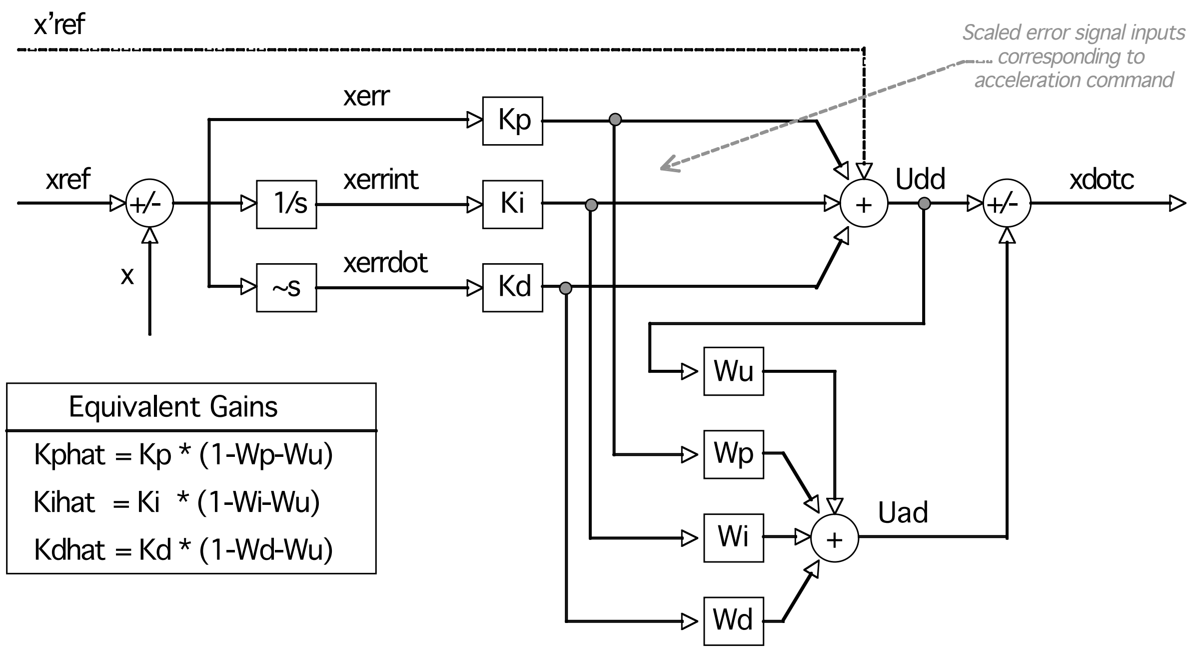


In the case of piloted aircraft, the neural networks must be capable of adapting quickly enough to assist pilots in controlling a damaged aircraft. However, they must also avoid transients that could interfere with the pilot's ability to control the aircraft. As a result, the neural network configuration and selection of inputs become critical factors for successful implementation of a neural network-based flight control system. For this application, modifications were made to the configuration of the sigma-pi neural networks to achieve the goals of reducing transients upon failure insertion, improving tracking and reducing cross-coupling effects during failures, while maintaining the ability to analyze and preserve the stability margins of the adaptive system.

A two-layer sigma-pi neural network is used for each channel. The first layer can be described as finding the features, while the second layer generates weighted polynomial combinations of those features. One characteristic of the sigma-pi neural network is global function approximation, which has the benefit of not having to relearn failures at different flight conditions. However, as a result, the network also tends to have a short-term memory effect and therefore needs to constantly adapt to changing flight conditions in order to be effective.

Inputs into the network consist of bias terms, sensor feedback, and control commands.

- *Bias terms* are used as inputs to compensate for out-of-trim conditions caused by damage or failures. For example, in the case of an offset right stabilator failure, the integrators in both the pitch and roll axis need to build up in order to compensate for the offset. As long as the integrated error remains non-zero, it will have an effect on the adaptation law causing the weights to adapt. As a result, the roll of the bias term is to drive the integrated error back down to zero in the event of out-of-trim conditions.
- *Sensor feedback* is used to provide the necessary aircraft state information for compensating for unmodeled aircraft effects, by essentially introducing additional feedback loops when necessary. For example, if a failure causes a change in the aircraft's pitching moment due to angle of attack, then the neural network can use the angle of attack input to compensate for the error caused by the resulting inaccuracies in the model inversion.
- *Acceleration commands*—and their proportional, integral, and derivative (PID) components—are used as inputs to allow the controller to reconfigure itself. By adapting the weights that correspond to these inputs, the neural networks can essentially have the effect of adapting the equivalent PID gains and the neural network can be configured as to what extent it will be trained on integral, proportional, and derivative error. Furthermore, since the adaptation gain can be used to specify the overall rate of adaptation, the adaptation law gains can be viewed as specifying the relative rates of adaptation.



The pilot commands roll rate and aerodynamic normal and lateral accelerations through stick and rudder pedal inputs. These commands are then transformed into body-axis rate commands, which also include turn coordination, level turn compensation, and yaw-dampening terms. First-order reference models are used to filter these commands in order to shape desired handing qualities. Errors in roll rate, pitch rate, and yaw rate responses can be caused by inaccuracies in aerodynamic estimates and model inversion. Unidentified damage or failures can also introduce additional errors. In order to achieve a rate-command-attitude-hold (RCAH) system, a proportional-integral (PI) error controller is used to correct for errors detected from roll rate, pitch rate, and yaw rate feedback.

A daisy-chain control allocation technique is used to ensure that conventional flight control surfaces will be utilized under normal operating conditions. Under damage or failure conditions, the system may utilize unconventional flight control surface allocations, along with integrated propulsion control, when additional control power is necessary for achieving desired flight control performance. Of significant importance here is the fact that this system can operate without emergency or backup flight control mode operations. An additional advantage is that this system can utilize, but does not require, fault detection and isolation information or explicit parameter identification.

2. SIGNIFICANCE.

a. Explain why the contribution is significant: scientifically, technologically, or from a humanitarian viewpoint, to the aeronautics, space community, and non-aerospace commercial activities.

This innovative technological achievement represents a potentially major advance in aircraft safety. "Loss of control" is a leading and complex aircraft accident category. Over the period 1987-2004 it resulted in 2524 fatalities (approximately 27% of total air fatalities) across the worldwide commercial jet fleet. Numerous causal and contributing factors can be cited for these accidents, with multiple factors often combining to result in loss of control. Historical and emerging causal and contributing factors can be categorized as adverse conditions (including system and component faults and failures, vehicle impairment and damage, vehicle configuration incompatibilities, software and hardware errors, crew input errors, and inappropriate crew response), vehicle upset conditions (including operation beyond the normal flight envelope, unstable modes of motion, stall and/or departure from controlled flight, uncommanded motions due to asymmetric thrust, failures, damage, and out-of-control motions), and external hazards (including icing conditions, wake vortices, turbulence, and wind shear).

Conventional flight control systems require extensive gain scheduling for a large number of operating points within the aircraft flight envelope to accurately respond to the full range of possible variables. When such a controller must be extended to account for actuator failures, a complete redesign is required for each anticipated failure case at all the gain schedule operation points. The many types of failures that can be envisioned would lead to a very large scheduling table, making such a controller both difficult to design and difficult to implement in real time. In addition, a truly fault-tolerant control system must also be able to accommodate non-anticipated failures, which would not be included in even very extensive scheduling tables.

Neural network-based adaptive flight control, within the setting of feedback inversion control, has been shown to require no gain scheduling and is only minimally model dependent. Hence, it provides an attractive candidate flight control architecture to ensure flight safety in the presence of unknown actuator failures. Over the past several years, this research project has been increasing the technology readiness level of this type of approach during a series of low- to medium-fidelity simulations, and more recently on small-scale unmanned aerial vehicle flight tests.

The recent 2005 and early 2006 flight tests of the Gen II neural networks, performed on a modified F-15 aircraft, represent the first piloted evaluation of this technology. The Gen II innovations allow the neural networks to adapt sufficiently fast to assist pilots in controlling a damaged aircraft while attempting high-performance maneuvers, without interfering with the pilot’s ability to control the aircraft. Furthermore, these innovations provide the increased stability required to overcome higher technology readiness level implementation issues such as signal time delays and aeroservoelastic compensation, designed to filter flexible body effects from flight control sensors.

Second-generation IFCS technology directly addresses the majority of “loss of control” issues identified by the aeronautics community, as well as loss-of-control conditions experienced by military aircraft under both test and combat conditions. It is also directly extensible to many space-based and non-aerospace applications that are operated in uncertain, hazardous, and complex environments.

When successfully matured and commercialized, this technology will provide the humanitarian benefit of lives saved in aviation mishaps, along with a substantial increase in overall aircraft safety. Its commercial adoption would represent a major competitive advantage for the national aerospace industry. In addition, neural network-based adaptive flight control could have significant applications in a number of other aeronautics and aerospace domains, including Uncrewed Aerial Vehicles (UAVs), robotic spacecraft, and the future generations of NASA’s crewed space vehicles.

b. Estimate the degree of scientific or technological significance by a mark on the line below:

0__________1______________2__________________3________________4________________5

None ***Modest*** ***Average*** ***Major*** ***Maximum***

c. Estimate the significance of the contribution relative to a specific NASA program or mission by marking the line below:

0__________1______________2__________________3________________4________________5

None ***Modest*** ***Average*** ***Major*** ***Critical***

3. **STAGE OF DEVELOPMENT.**

Indicate the stage of development of the contribution by a mark on the line below:

0___________1_______________2___________________3_________________4_________________5

Concept ***Simulated*** ***Tested*** ***Fully Developed*** ***Operational***

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4. **ASSESSMENT OF USE.**

   a. *If the contribution is now in operation, describe its performance and value within both the aerospace field and its application to non-aerospace commercial and government uses.*

This contribution is in the experimental stage of development and is not in production on piloted aircraft. It is not known if this application is in operation on military tactical missile systems.

   b. *If the contribution is not now in operational use, describe its most likely or previous applications and the extent of commercial, (includes non-aerospace commercialization) government and/or NASA-specific uses.*

The Intelligent Flight Control System project at NASA's Dryden Flight Research Center has demonstrated the benefits of adaptive control laws in the piloted fly-by-wire canard-equipped F-15B. The project induced simulated aerodynamic and surface failures and obtained improved flying qualities with an adaptive system engaged. This has demonstrated a way to efficiently optimize aircraft performance and increase safety under both normal and failure conditions. The neural network is an assistive technology that does not interfere with the pilot's normal control functions, and thus is directly applicable to existing commercial and government aircraft.

As described in section 1b, there are a number of other likely applications of this neural network-based flight control technology for new aerospace systems designs. These include crewed and uncrewed systems, both for military and commercial aviation applications. Many vehicle classes are being considered within the aerospace community, including commercial, fighter, transport aircraft, unmanned air vehicles, and spacecraft. Non-aerospace applications of this type of intelligent software can be used in power plants, automobiles, and other less complicated systems to avoid disasters after equipment failures.

Future NASA-specific applications include:

- Aeronautics Research Mission Directorate – Aviation Safety Program/Integrated Resilient Aircraft Control Project. This contribution was recently cited in a $165M/5-year Project Proposal in Integrated Resilient Aircraft Control to NASA's Aeronautics Research Mission Directorate's Aviation Safety Program.
- Science Mission Directorate – Sub-orbital Science Program/Earth Science Capability Demonstration Project. This contribution is currently being considered as part of the Civil UAV Capabilities Assessment (part of Autonomous Mission Management, Contingency Management, and Reliable Flight Systems): http://www.nasa.gov/centers/dryden/research/civuav/index.html

   c. *Will the contribution increase in value or in its applications over time and in what manner?*

The contribution will increase in value if used by larger numbers of aircraft, and in will increase in its application across different sectors (e.g. "tactical/military-to-practical/civilian"). The results of a cost/benefit assessment by SRS Technologies, using the Air Force C-17 aircraft as the basis for the analysis, indicated the following benefits:

- 25% to 30% savings in software development time
- >70% reduction in control effectiveness testing in wind tunnels
- 1500 lb empty weight reduction via reduced redundancy requirements to achieve equivalent or improved levels of safety.

Analysis indicates savings can be made in the following areas:

- Flight Control System: Eliminate Mechanical Linkages, Eliminate Cabling, Actuators
- Avionics: Eliminate Black-Boxes

- Electronics: Reduced Power Requirements
- Environmental Control: Reduced Cooling Requirements

Source: "C-17 Neural Flight Control System Benefit Assessment", SRS Technologies

5. CREATIVITY.

What is your assessment of the creativity displayed in the conduct of this contribution, relative to the expected performance of those in similar positions?

*None*________*Low* __________*Modest*_________*Average*________*High*_________*Very High*____________

6. RECOGNITION

What forms of recognition have been received by the contributors for this contribution? Have previous awards been made to the contributor(s) for this accomplishment? Please describe.

Previous awards and recognition received for this contribution occurred primarily during early development, following successful piloted flight simulation experiments that allowed the technology to be matured for flight validation:

- 2002 Presidential Rank and Honor Award, Exceptional Service Medal, K. Gundy-Burlet.
- 2001 Presidential Rank and Honor Award, Exceptional Service Medal, C. Charles Jorgensen.
- 2001 Presidential Rank and Honor Award, Integrated Neural Flight and Propulsion Control System, Intelligent Flight Control Group, John Kaneshige, Karen Gundy-Burlet, Don Soloway, and Don Bryant.
- 1999 National 1999 Discover 100 Award Finalist, C. Charles Jorgensen (Transportation Category).
- 1998 Ames Honor Award, Category of Engineer, Joseph Totah.
- 1998 NASA Honor Award, Intelligent Flight Control, Group Achievement Award.

7. TANGIBLE VALUE.

As a measure of the tangible value of this contribution, estimate the following:

a. NASA cost savings to date and in future years.*

NASA has not realized cost savings to date, however there is expected benefit derived from this capability in the future. The savings would mostly be realized within the Aeronautics Research Mission Directorate for new aircraft concept testing (via wind tunnels and flight simulators) and experimental aircraft (manned and unmanned), in all flight regimes (subsonic through hypersonic). Savings estimates, based on the SRS Technologies C-17 report, are provided in section 4c. Other mission directorates within NASA that require missions in uncertain, hazardous, and complex environments would benefit from this capability, as well.

**State the rationale for the above cost estimates*.

b. Current market value and potential as a commercial product or process.

This technology has great deal of potential market value as a commercial product. A survey conducted by SRS Technologies in March 2002, based on data obtained from the Air Force Safety Center located at Kirkland Air Force Base, collected data from 1981-2000 for a representative set of operational aircraft (specifically, the A-10, B-1, B-52, C-130, C-141, F-15, F-16, F-117, T-37, T-38, H-1, and H-60). The study revealed that a total of 495 accidents (in all categories) occurred related to the Flight Control System over 37M flight hours, with a total of 30 deaths (out of 586).

The report further investigated whether newer flight control system (FCS), technologies (not including the Gen II neural network described in this application) had any impact on these accident rates during the latter part of the period studied. The SRS report indicated that "data for all FCS accidents over this 20 year period [1981-2000] was compared to total FCS accident rates for the latter 5 years to see if the insertion of new FCS technologies impacted accident rates. Cat-A-C accident rates were 1.33x10-6 and 1.26x10-6 per flight hr for the 20-year period and the latter 5 year period, thus no discernable difference was detected."

This finding clearly illustrates the need for a technological advance in flight control systems that can have a positive effect on these accident and fatality rates. IFCS capability has the potential for a tremendous impact by improving this accident rate, saving lives, and reducing costs associated with catastrophic accidents attributable to the flight control system. It is not difficult to imagine the increased marketing potential for future aircraft equipped with the advanced control characteristics and improved survivability from mishaps that would be afforded by this neural network technology.

c. *Other measurable value: increased efficiency, enabling technology, improved management, etc.*

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- Environmental Control: Reduced Cooling Requirements

APPLICANT'S SIGNATURE: ____DATE:_____________